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# Emergy evaluation of the performance and sustainability of three agricultural systems with different scales and management

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**Abstract**

Emergy analysis was used to analyze three agricultural systems to compare and contrast resource use, productivity, environmental impact, and overall sustainability. Emergy analysis was appropriate for this task because of its ability to transform different types of inputs to a common form (solar energy equivalents) to allow meaningful comparisons across the three systems. The systems analyzed were conventional corn (*Zea mays* L.) production in Kansas, USA, blackberry (*Rubus rubus* Watson) production in Ohio, USA, and a Lacandon polycultural rotation system in Chiapas, Mexico. Despite these different systems and diverse inputs, emergy allowed the quantification and comparison of flows for each system on a common basis. This allowed system-level conclusions and demonstrated the utility of emergy analysis when evaluating agricultural systems. The greatest inputs of emergy across the three systems were for fertilization and irrigation of the corn system. These two inputs accounted for 95% of the purchased emergy input to the corn system. The indigenous system was most reliant on renewable resources, and therefore, had the lowest level of environmental loading. The sustainability index for the three systems ranged from 0.06 for the corn system, to 0.65 for the blackberry system, to 115.98 for the indigenous system. The respective energy and emergy yield for each system were 2.6E9 J $ha^{-1}$ $year^{-1}$ and 3.57E15 sej $ha^{-1}$ $year^{-1}$ for the indigenous system, 3.71E10 J $ha^{-1}$ $year^{-1}$ and 8.59E15 sej $ha^{-1}$ $year^{-1}$ for the blackberry system, and 1.40E11 J $ha^{-1}$ $year^{-1}$ and 1.30E16 sej $ha^{-1}$ $year^{-1}$ for the corn system. While the indigenous system has the highest level of sustainability, its energy yield was 14 times less than the blackberry system, and 53 times less than the corn system. The results confirm the need for food production systems with large yields that are more dependent on renewable energies.


*Keywords:* Resource use; Production; Environmental impact; Corn; Maize; Blackberry; Lacandon Maya

## 1. Introduction

An important challenge facing the world is how to feed an increasing population with decreasing energy supplies and finite environmental resources. To meet this challenge the sustainability of agricultural methods must be evaluated to determine those with greater yields relative to their resource use and environmental degradation. Processes using larger percentages of renewable energy need to be identified because they are likely to be more sustainable than those using a larger percentage of non-renewable energy (Lefroy and Rydberg, 2003; Martin, 2002). Therefore, to increase agricultural sustainability the trend of increasing production with greater non-renewable inputs, which characterized the Green Revolution (Ko et al., 1998), should be ended.

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Additionally, adverse environmental consequences of food production, such as soil erosion and declining water tables, must be reduced to insure that future production is not jeopardized (Pimentel et al., 1995).

Agriculture operates at the interface between nature and the human economy and combines natural resources and economic inputs to produce food. Typically, high quality, non-renewable energies from the human economy are utilized to capture and concentrate lower quality, renewable energies. Intensive agricultural methods rely more on resources purchased from the economy, while less intensive and indigenous methods typically rely more on natural inputs. Because most types of agriculture depend on a combination of natural and economic inputs, it is necessary to account for both in equivalent terms when comparing the resource use of agricultural methods (Campbell, 1998). While the value of economic contributions is routinely quantified by economic analyses, such approaches often underestimate environmental contributions to production systems. If environmental inputs are not properly accounted for relative to economic inputs, optimum use of resources may not be achieved, and management decisions will be based on incomplete analyses (Ulgiati et al., 1994). For example, Faeth et al. (1991) analyzed the net income of a Pennsylvania, USA soybean–corn farm with and without natural resource accounting. A net annual income of US\$200 $ha^{-1}$ without accounting for natural resources was reduced to US\$137.5 $ha^{-1}$ when the degradation of natural resources was included, largely in the form of soil erosion. Studies of this type highlight the need for integrated approaches to quantify economic and environmental inputs, to select sustainable systems to meet future needs (Lefroy and Rydberg, 2003).

Emergy analysis, which evaluates system components on a common unit basis, is a promising tool to evaluate resource use and production of agricultural methods. Emergy analysis is a form of energy analysis that quantifies values of natural and economic resources to quantify the value of large-scale environmental support to the human economy (Odum, 1988). It is viewed a 'donor-side' evaluation approach because it values items based on energetic inputs as opposed to consumer preferences. Solar emergy is used to determine the value of environmental and human work within a system on a common basis: the equivalent solar energy required to produce each service or product. The fundamental assumption of emergy analysis is that the contribution of a resource is proportional to the available energy of one kind required to produce the resource (Brown and Herendeen, 1996). The solar emergy of products and services is calculated by multiplying units of energy (i.e. joules of oil) by emergy per energy ratios (transformities), units of mass (i.e. grams of corn) by emergy per mass ratios (specific emergy), and dollars by emergy per unit money. Using this technique, natural and economic contributions required to produce agricultural yields can be quantified and compared on a common basis of solar emergy-joules (emjoules). Emergy analysis has been used in a similar capacity to quantify economic and environmental inputs to water projects on the Mississippi and Mekong rivers (Martin, 2002; Brown and McClanahan, 1996), and to evaluate the sustainability of agricultural methods in Australia (Lefroy and Rydberg, 2003), Sweden (Rydberg and Jansen, 2002), Italy (Ulgiati et al., 1994), and China (Hong-fang et al., 2003).

The goal of this study was to compare three different agricultural systems with regard to their resource use, productivity, environmental impact, and overall sustainability. The three systems were corn (*Zea mays* L.) production in Kansas, United States, blackberry (*Rubus Rubus* Watson) production in Ohio, United States, and polyculture production in Chiapas, Mexico. These systems included a highly productive, conventional United States farm (Kansas corn), a family run "pick your own" fruit cultivation (Ohio blackberry), and a subsistence-based indigenous swidden system (Chiapas polyculture).

## 2. Methods

### 2.1. Site descriptions

The study site for the corn analysis was 89 ha of a furrow irrigated family owned farm located in Republic County, Kansas, USA (39°49′28″N 097°37′56″W). The corn production was rotated on a three-year cycle with sorghum. While this analysis focused only on corn production for one year, the benefits of crop rotation were accounted for by reduced annual rates of fertilizer, herbicide, and insecticide application.

The blackberry farm consisted of 0.11 ha in which blackberries grew with 1.3 m spacing in rows that were 3.3 m apart to allow for tractor access. Located near, Columbus, Ohio, USA (39°57′40″N 082°59′56″W), the family owners have successfully allowed customers to self-harvest the produce.

Traditional Lacandon Maya agroecosystems of Chiapas, Mexico (16°45′30″N, 91°30″W) cycle through three stages of production starting with the milpa (field crop stage), progressing to the acahual (bush stage), and then to the forest, before returning to the milpa. Each farmer typically divides their total area into milpas, acahuals and forests of different ages. Natural ecological succession drives the conversion between field stages (McGee, 2002, p. 82; Nations and Nigh, 1980). Polyculture is used in each field stage with as many as 60 different plant species producing resources. By directing natural succession through the control of seed banks and plantings and using resources from all stages during this progress, the Lacandon are able to reap benefits from their fields without inputs of seeds, fertilizer, herbicides, and pesticide (Levy, 2000). For this analysis a total area of 12 ha was analyzed that contained 2 ha of milpa and 10 ha divided between acahual and forest plots.

The three systems represent a wide range of spatial scale and socio-economic settings that affect resource use and sustainability. The corn and blackberry systems are characterized by high labor costs compared to the indigenous system, and the need to make an economic profit. The high cost of labor provides an incentive to invest in equipment, such as tractors, and materials, such as herbicides, that can be utilized with little labor. For instance, herbicides are a method of weed control that reduce labor inputs compared to manual weed removal employed in the indigenous system. This strategy allows the corn farmers to crop a large area with little labor input. The blackberry system confronts high labor costs by producing a high-value crop and having consumers harvest the product. Because the operation is located near a metropolitan area, this strategy is successful. Currently, in the subsistence system there are low opportunity costs for labor. This allows farmers, and other family members to devote large amounts of time to their agricultural systems as opposed to US farmers. However, the area of these systems is limited by the amount of land a farmer and family members can maintain. Government subsidies are another socio-economic factor that affect the corn and indigenous systems differently. Government payments in the event of crop failure, give the farmer the security of a minimal return in the event of crop failure. This 'insurance' facilitates corn monocultures, and maximizes yields. With no government payments in the event of crop failures, the indigenous system must hedge against possible crop failure with a multi-species system. The result for the indigenous system is lower yields, but decreased chances of complete crop failure. Because the indigenous system is a subsistence system, there is no need to produce an economic product, which also favors multicropping as opposed to maximizing yields and economic profits.

### 2.2. Fundamental terms of emergy analysis (Brown and Ulgiati, 2004)

*Emergy*: The available energy (exergy) of one kind that is used in the transformations directly and indirectly to make a product or service. Emergy is measured in emjoules. Sunlight, fuel, electricity, and human service and all other resource flows can be put on a common basis by expressing them in the emjoules of solar energy required to produce them, which is expressed as solar emjoules (sej). While other units, such as coal emjoules, were used in the past, recent emergy studies track resource flows in solar emjoules.

*Transformity*: The ratio of emergy input to available energy (exergy) output. For example, the solar transformity of wood is 4000 solar emjoules per joule (sej $J^{-1}$) because 4000 solar emjoules of environmental inputs were required to generate a joule of wood. The solar transformity of sunlight absorbed by the earth is defined as 1 sej $J^{-1}$. Transformities have been calculated for a wide variety of resources, commodities, and renewable energies, and can be found in past publications (e.g., Odum, 1996, pp. 304–311), and a series of emergy folios (Brandt-Williams, 2002; Kangas, 2002; Brown and Bardi, 2001; Odum, 2000; Odum et al., 2000).

*Specific emergy*: The emergy per unit mass output. This is usually expressed as solar emergy per gram (sej $g^{-1}$).

*Emergy per unit money*: The emergy supporting the generation of one unit of economic product (expressed as currency). The average emergy/money ratio sej US$$^{-1}$) can be calculated by dividing the total emergy use of an economy by its gross economic product (e.g., GDP).

*Empower:* The flow of emergy per unit of time. Emergy flows are usually expressed in units of solar empower (i.e. sej $year^{-1}$). To compare the empower of different areas this quantity can be divided by area to calculate empower per area (i.e. sej $year^{-1}$ $ha^{-1}$).

### 2.3. Emergy analysis

Aggregated system diagrams (Fig. 1) illustrate the main components and interactions for each of the agricultural methods. Tables 1–3 denote the specific input flows that comprise the renewable resources, non-renewable resources, and purchased resources identified for each system in Fig. 1. Non-renewable resources may include soil, groundwater, and any other environmental resources not replaced within an annual cycle. Examples of purchased resources include fuel, electricity, fertilizer, irrigation water, chemicals, machinery, and labor. After quantifying annual inputs to each system in raw units (joules, grams, dollars), these values were multiplied by transformities to calculate the quantity of solar emjoules required for each input (Tables 1–3). To make these flows easily comparable, the last column of Tables 1–3 was normalized for area and quantified these values in solar emjoules per hectare per year (sej $ha^{-1}$ $year^{-1}$). The transformities used in this study include labor and services required to produce economic goods. The transformities for each product do not include inputs required for harvest and transport, and represent the amount of inputs required to generate a harvestable product on the farm.

Additional explanation is required for the irrigation inputs and labor transformities used in Table 1. Because the groundwater withdrawal rate for the blackberry system, 10.1 cm $year^{-1}$, was well below the recharge rate of the aquifer, irrigation water was included as a renewable resource. In contrast, the withdrawal rate for the corn system, 38.1 cm $year^{-1}$, was well above the recharge rate of the aquifer, and therefore, irrigation water was included as a non-renewable resource. In both the corn and blackberry systems, electricity that was needed to extract water from the aquifer was included as a purchased resource. Labor was a necessary input to all three systems. The transformity of labor is dependent on the amount of emergy needed to support the laborer. Labor in more developed countries and by more educated laborers, will have greater transformities than labor in less developed nations and by less educated

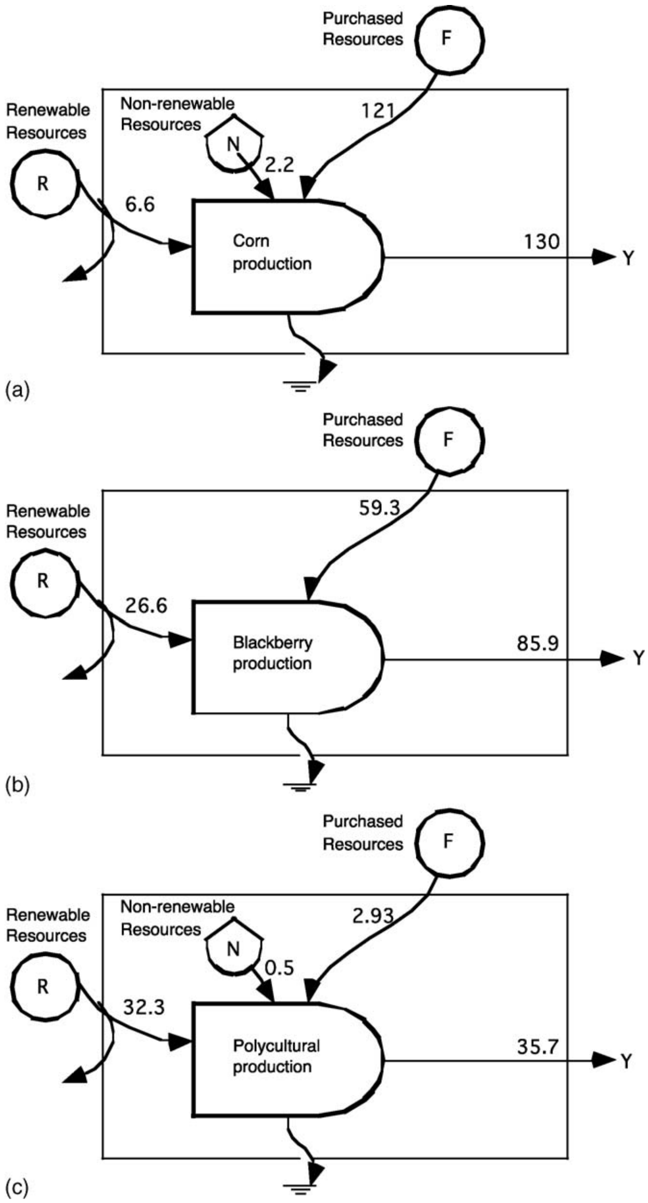



Fig. 1. Summary diagrams of the emergy flows in the three agricultural systems: (a) corn, (b) blackberry and (c) indigenous polyculture. All emergy flows are $10^{14}$ sej ha$^{-1}$ year$^{-1}$. The letters R, N ,F, and Y correspond to the calculation of indices in Table 4.

laborers. These differences were reflected in the transformities used to quantify the amount of solar emjoules needed to support the labor for each system. The corn system laborers had college educations, which corresponded to a transformity of 8.80E12 sej h$^{-1}$ (Table 1; Ortega, 2000). High school students provided most of the labor in the blackberry system, which corresponded to a transformity of 1.12E12 sej h$^{-1}$ (Table 1; Ortega, 2000). The labor in the Lacandon polycultural system was provided by a 50-year-old farmer. The age of the farmer resulted in a labor transformity (6.99E12 sej h$^{-1}$; Guillen-Trujillo, 1998) greater than that for the blackberry system, but less than that for the corn system.

The percentage of renewable and non-renewable emergy supporting labor in each of the systems (Ulgiati et al., 1994) was determined based on previous studies. In Sweden and Italy, two countries with living standards similar to the United States, 87% and 90%, respectively, of the emergy supporting labor was due to non-renewable sources (Panzieri et al., 2002; Rydberg and Jansen, 2002). Following the Swedish study, 87% of the emergy supporting labor was assumed to be non-renewable, and 13% was assumed to be renewable for both systems in the United States. The non-renewable and renewable percentages of emergy supporting labor were 23% and 77%, respectively, for the indigenous system in Lacanja, Chiapas, Mexico. Guillen-Trujillo (1998) calculated these percentages for agricultural households in Frontera Corozal, Chiapas, which is located near Lacanja.

Emergy indices (Hong-fang et al., 2003; Brown and McClanahan, 1996; Table 4) were calculated by aggregating data from Tables 1–3. These Indices, which relate flows from the economy to flows of the environment, were used to compare net yields and environmental loading, and to identify more sustainable agricultural methods. The fraction renewable index (Table 4) quantified the reliance of each system on renewable energies. The emergy yield ratio (Table 4) compared units of exported emergy with emergy invested. For agriculture, an investment of emergy from the economy is made in order to capture renewable emergy from the environment. This ratio quantifies the effectiveness of non-renewable resources to capture renewable resources. The environmental loading ratio (Table 2) is the ratio of purchased and non-renewable resources to renewable resources. It may also be considered a ratio of emergy under human control (non-renewable local inputs and purchased inputs) and free, renewable emergy. It is an indicator of the pressure of agricultural systems on the environment and may be considered a measure of ecosystem stress due to agricultural production (Ulgiata and Brown, 1998). It should be pointed out that portions of the ecosystem stress may occur to regions outside the area of analysis. An example is phosphate fertilizer, which causes ecosystem stress at the mining site before being used on a distant farm. The emergy sustainability index (Table 4) was calculated as the ratio of the emergy yield ratio to the environmental loading ratio, and measures the production of a system relative to the environmental pressure (Ulgiata and Brown, 1998).

To analyze the effects of variations in transformities and input quantities, a sensitivity analysis was performed that quantified the effects of varying the yearly emergy inputs (the final column in Tables 1–3). Because the yearly emergy input is the product of the transformity and yearly input, varying the yearly emergy tests the sensitivity of the results to variations of both transformities and yearly inputs. As suggested in modeling texts (Odum and Odum, 2000, p. 142), the effect of doubling and halving the yearly emergy values upon the indices was quantified.

Table 1
Emergy contributed by each flow in the corn system (89 ha) was calculated by multiplying the units per year entering each system by its respective transformity

| Number | Item | Value (unit year$^{-1}$) | Transformity (sej unit$^{-1}$) | Emergy (sej year$^{-1}$) | Emergy (sej ha$^{-1}$ year$^{-1}$) |
|---|---|---|---|---|---|
| Renewable resources | | | | | |
| 1 | Sunlight (j year$^{-1}$) | 3.95E+15 | 1.00E+00 | 3.95E+15 | 4.44E+13 |
| 2 | Wind (j year$^{-1}$) | 2.66E+13 | 1.50E+03 | 3.99E+16 | 4.49E+14 |
| 3 | Rain (j year$^{-1}$) | 3.18E+12 | 1.82E+04 | 5.79E+16 | 6.50E+14 |
| 4 | Labor (renew)(h year$^{-1}$) | 4.40E+02 | 8.80E+12 | 5.03E+14 | 5.66E+12 |
| Total renewable | | | | 5.84E+16 | 6.56E+14 |
| Non-renewable resources | | | | | |
| 5 | Soil (j year$^{-1}$) | 3.07E+11 | 6.25E+04 | 1.92E+16 | 2.16E+14 |
| Total non-renewable | | | | 1.92E+16 | 2.16E+14 |
| Purchased resources | | | | | |
| 6 | Diesel fuel (j year$^{-1}$) | 1.71E+11 | 6.60E+04 | 1.13E+16 | 1.27E+14 |
| 7 | Electricity (j year$^{-1}$ | 3.02E+10 | 2.00E+05 | 6.04E+15 | 6.79E+13 |
| 8 | Nitrogen (g year$^{-1}$) | 1.80E+07 | 2.41E+10 | 4.34E+17 | 4.87E+15 |
| 9 | Phosphorus (g year$^{-1}$) | 3.49E+06 | 2.20E+10 | 7.68E+16 | 8.63E+14 |
| 10 | Sulfur (g year$^{-1}$) | 9.98E+05 | 9.13E+07 | 9.11E+13 | 1.02E+12 |
| 11 | Irrigation water (gal year$^{-1}$) | 8.96E+07 | 5.84E+09 | 5.23E+17 | 5.88E+15 |
| 12 | Seeds (j year$^{-1}$) | 2.56E+10 | 3.64E+05 | 9.32E+15 | 1.05E+14 |
| 13 | Herbicide (g year$^{-1}$) | 8.73E+04 | 1.48E+10 | 1.29E+15 | 1.45E+13 |
| 14 | Insecticide (g year$^{-1}$) | 6.09E+05 | 1.48E+10 | 9.01E+15 | 1.01E+14 |
| 15 | Machinery (US$ year$^{-1}$) | 4.40E+03 | 1.37E+12 | 6.03E+15 | 6.77E+13 |
| 16 | Labor (non-renew) (h year$^{-1}$) | 4.40E+02 | 8.80E+12 | 3.37E+15 | 3.78E+13 |
| Total purchased | | | | 1.08E+18 | 1.21E+16 |
| Exported items (Y) | | | | | |
| 17 | Feed corn | 8.38E+05 kg year$^{-1}$<br>1.25E+13 J year$^{-1}$ | | | 9.42E+03 kg ha$^{-1}$<br>1.40E+11 J ha$^{-1}$ |

Transformity references for respective row number: 2. Odum, 1996, 3. Odum, 1996, 4. Ortega, 2003, 5. Ulgiati et al., 1994, 6. Odum, 1996, 7. Ulgiati et al., 1994, 8. Brandt-Williams, 2002, 9. Brandt-Williams, 2002, 10. Odum et al., 2000, 11. Buenfil, 2000, 12. Trujillo, 1998, 13. Brandt-Williams, 2002, 14. Brandt-Williams, 2002, 15. Odum, 1996, 16. Ortega, 2003.

## 3. Results

### 3.1. Renewable resources

Due to the contribution of groundwater, the blackberry system had the greatest input of renewable resources (2.66E15 sej ha$^{-1}$ year$^{-1}$, Table 4). The Lacandon polycultural system had the second greatest amount of renewable emergy inputs per hectare (3.23E15 sej ha$^{-1}$ year$^{-1}$, Table 4). This was because this system had the greatest amount of annual rainfall (2.5 m year$^{-1}$) which accounted for 2.25E15 sej ha$^{-1}$ year$^{-1}$ (Table 3; Fig. 1). For all three study sites, the rain input was the largest of the climatological renewable emergy sources (Tables 1–3; Fig. 1), and was taken to represent the total climatological renewable flows. This was done to avoid double counting, because all the climatological renewable energy flows are by-products of coupled processes (Lefroy and Rydberg, 2003; Odum, 1996, pp. 51–52). Therefore, the total renewable input for the corn system was 6.56E14 sej ha$^{-1}$ year$^{-1}$, respectively (Table 4). Seeds were included as a renewable input for the polycultural system (Table 3). This was because the seeds for the fallow fields are contributed by adjacent forested areas, and because the Lacandon produce the seeds for cultivated crops from previous years' harvests.

### 3.2. Non-renewable resources

Non-renewable resources used in the form of soil erosion (5.0 kg ha$^{-1}$ year$^{-1}$; NRCS, 2000) totaled 2.16E14 sej ha$^{-1}$ year$^{-1}$ (Table 1) for the corn system. The polycultural system had a soil erosion rate of 7 tons ha$^{-1}$ year$^{-1}$ for the milpa areas. The acahual and forest areas have dense cover and a detritus layer that effectively eliminates soil erosion. The total loss from the system of 14 tons of soil per year resulted in an input of non-renewable resources of 4.58E13 sej ha$^{-1}$ year$^{-1}$ (Table 3). Because no appreciable soil erosion occurs in the blackberry system, non-renewable inputs were assumed to be zero.

### 3.3. Purchased resources

Across the three systems the largest inputs in this category were irrigation water, fertilizer, fuel, and labor. The greatest input into any of the systems was the irrigation water needed for corn production (Fig. 1). The large amount of emergy associated with this flow was due to both the

Table 2
Emergy contributed by each flow in the blackberry system (0.11 ha) was calculated by multiplying the units per year entering each system by its respective transformity

| Number | Item | Value (unit year$^{-1}$) | Transformity (sej unit$^{-1}$) | Emergy (sej year$^{-1}$) | Emergy (sej ha$^{-1}$ year$^{-1}$) |
|---|---|---|---|---|---|
| Renewable resources | | | | | |
| 1 | Sunlight (j year$^{-1}$) | 4.88E+12 | 1.00E+00 | 4.88E+12 | 4.44E+13 |
| 2 | Wind, KE (j year$^{-1}$) | 1.47E+09 | 1.50E+03 | 2.20E+12 | 2.00E+13 |
| 3 | Rain (j year$^{-1}$) | 5.40E+09 | 1.82E+04 | 9.83E+13 | 8.93E+14 |
| 4 | Labor (renew) (h year$^{-1}$) | 1.49E+02 | 1.12E+12 | 2.17E+13 | 1.97E+14 |
| 5 | Irrigation water (gal year$^{-1}$) | 2.95E+04 | 5.84E+09 | 1.72E+14 | 1.57E+15 |
| Total renewable | | | | 2.92E+14 | 2.66E+15 |
| Purchased resources | | | | | |
| 6 | Irrigation electricity (gal year$^{-1}$) | 2.95E+04 | 1.20E+09 | 3.54E+13 | 3.22E+14 |
| 7 | Gasoline (j year$^{-1}$) | 1.98E+09 | 1.11E+05 | 2.20E+14 | 2.00E+15 |
| 8 | Herbicides (g year$^{-1}$) | 4.26E+02 | 1.48E+10 | 6.30E+12 | 5.73E+13 |
| 9 | Insecticides (g year$^{-1}$) | 1.49E+03 | 1.48E+10 | 2.21E+13 | 2.00E+14 |
| 10 | Fungicides (g year$^{-1}$) | 2.95E+02 | 1.48E+10 | 4.37E+12 | 3.97E+13 |
| 11 | Pheromone traps (g year$^{-1}$) | 1.41E+03 | 3.20E+09 | 4.51E+12 | 4.10E+13 |
| 12 | Fertilizer (N) (g year$^{-1}$) | 6.24E+03 | 2.41E+10 | 1.50E+14 | 1.37E+15 |
| 13 | Tools | 9.58E+03 | 6.70E+09 | 6.42E+13 | 5.84E+14 |
| 14 | Labor (non-renew) (h year$^{-1}$) | 1.49E+02 | 1.12E+12 | 1.45E+14 | 1.32E+15 |
| Total purchased | | | | 6.52E+14 | 5.93E+15 |
| Exported items (Y) | | | | | |
| 15 | Blackberries | 1.57E+03 kg year$^{-1}$<br>4.08E+09 J year$^{-1}$ | | | 1.43E+04 kg ha$^{-1}$<br>3.71E+10 J ha$^{-1}$ |

Transformity references for respective row number: 2. Odum, 1996, 3. Odum, 1996, 4. Ortega, 2003, 5. Buenfil, 2000, 6. Buenfil, 2000, 7. Brandt-Williams, 2002, 8. Brandt-Williams, 2002, 9. Brandt-Williams, 2002, 10. Brandt-Williams, 2002, 11. Brown and Bardi, 2001, 12. Brandt-Williams, 2002, 13. Panzieri et al., 2002, 14. Ortega, 2002.

amount of water used (0.38 m year$^{-1}$) and the transformity of this resource (5.84E9 sej gal$^{-1}$, Table 1). This input accounted for 48% of the purchased inputs to the corn system. The second and third greatest purchased inputs of emergy to the corn system were due to nitrogen and phosphorus fertilizer (4.87E15 and 8.63E14 sej ha$^{-1}$ year$^{-1}$, Table 1), which accounted for 40% and 7%, respectively, of the total purchased resources. All other purchased inputs to the corn system accounted for 1% or less of the total purchased inputs (Table 1).

The emergy associated with purchased inputs to the blackberry system was more evenly distributed between different inputs compared to the corn system. In the blackberry system four purchased inputs contributed 10% or more of the total emergy for purchased resources. Gasoline, used for mowing and pruning, was the greatest purchased input and represented 34% of the total purchased inputs (2.00E15 sej ha$^{-1}$ year$^{-1}$, Table 2). The next largest purchased input was the non-renewable emergy contributing to labor, which accounted for 22% of the purchased inputs (Table 2). Nitrogen fertilizer and tools respectively accounted for 23% and 10% of the purchased resources. All other purchased resources accounted for 5% or less of the total emergy of purchased resources.

The polyculture system had only two purchased resources: labor and supplies. The amount of labor, 2180 h year$^{-1}$, was an order of magnitude greater for this system than the other systems. However, the relatively low percentage of non-renewable resources supporting labor (23%) resulted in a lower input of non-renewable emergy for labor compared to the blackberry system. The non-renewable resources supporting labor were an order of magnitude greater for the indigenous system compared to the corn system due to the greater number of hours worked in the indigenous system (Tables 1 and 3). The emergy contributed by supplies, which included machetes and axes, was more than two orders of magnitude less than the labor input (Table 3).

Due to the large emergy inputs from irrigation water and nitrogen fertilizer, the emergy for purchased resources per hectare was greatest for the corn system (1.21E16 sej ha$^{-1}$ year$^{-1}$, Table 4). The blackberry system had the second greatest input of purchased resources at 5.93E15 sej ha$^{-1}$ year$^{-1}$, or 49% of the corn purchased resources (Table 4). The polyculture system had the lowest input of purchased resources at 2.93E14 sej ha$^{-1}$ year$^{-1}$, or 1% of the corn system (Table 4).

### 3.4. Yields and transformities

The emergy assigned to the yield from the corn system, calculated by totalling renewable, non-renewable, and purchased inputs, was 1.30E16 sej ha$^{-1}$ year$^{-1}$ (Table 4). The corn yield from the system was 9.42E3 kg ha$^{-1}$ year$^{-1}$ or 1.40E11 J ha$^{-1}$ year$^{-1}$ (Table 1) which resulted in a transformity of 9.30E4 sej J$^{-1}$ (Table 4). The blackberry yield from the system was 1.43E4 kg ha$^{-1}$ year$^{-1}$ or

Table 3
Emergy contributed by each flow in the indigenous system (12 ha) was calculated by multiplying the units per year entering each system by its respective transformity

| Number | Item | Value (unit year$^{-1}$) | Transformity (sej unit$^{-1}$) | Emergy (sej year$^{-1}$) | Emergy (sej ha$^{-1}$ year$^{-1}$) |
|---|---|---|---|---|---|
| Renewable resources | | | | | |
| 1 | Sunlight (j year$^{-1}$) | 7.87E+14 | 1.00E+00 | 7.87E+14 | 6.56E+13 |
| 2 | Wind-kinetic (j year$^{-1}$) | 1.14E+10 | 1.50E+03 | 1.70E+13 | 1.42E+12 |
| 3 | Rain-chemical (j year$^{-1}$) | 1.48E+12 | 1.82E+04 | 2.70E+16 | 2.25E+15 |
| 4 | Seeds (j year$^{-1}$) | 2.64E+06 | 3.64E+05 | 9.60E+11 | 8.00E+10 |
| 5 | Labor (renew) (h year$^{-1}$) | 2.18E+03 | 6.99E+12 | 1.17E+16 | 9.78E+14 |
| Total renewable | | | | 3.87E+16 | 3.23E+15 |
| Non-renewable resources | | | | | |
| 6 | Eroded soil (j year$^{-1}$) | 8.79E+09 | 6.25E+04 | 5.49E+14 | 4.58E+13 |
| Total non-renewable | | | | 5.49E+14 | 4.58E+13 |
| Purchased resources | | | | | |
| 7 | Labor (non-renew) (h year$^{-1}$) | 2.18E+03 | 6.99E+12 | 3.50E+15 | 2.92E+14 |
| 8 | Supplies (US$ year$^{-1}$) | 6.00E+00 | 1.88E+12 | 1.13E+13 | 9.40E+11 |
| Total purchased | | | | 3.52E+15 | 2.93E+14 |
| Exported items | | | | | |
| 9 | Multiple products | | | | |
| | Corn (j year$^{-1}$) | 138E+10 *Zeamays* | | | |
| | Squash (j year$^{-1}$) | 3.13E+09 *Cucurbita* sp. | | | |
| | Chigua fruit | 5.00E+09 *Cucurbita* sp. | | | |
| | Chigua seed (j year$^{-1}$) | 3.36E+08 *Cucurbita* sp. | | | |
| | Cherry tomatoes (j year$^{-1}$) | 3.66E+08 *Lycopersicon esculentum* | | | |
| | Papaya | 1.24E+09 *Carica papaya* | | | |
| | Sugar cane (j year$^{-1}$) | 5.47E+08 *Saccharum officinarum* | | | |
| | Arrowroot (j year$^{-1}$) | 4.35E+07 *Maranta arundinacea* | | | |
| | Cassava (j year$^{-1}$) | 2.16E+09 *Manihot esculenta* | | | |
| | Onion (j year$^{-1}$) | 7.77E+08 *Allium cepa* | | | |
| | Mango (j year$^{-1}$) | 3.59E+09 *Mangifera indica* | | | |
| | Squash (j year$^{-1}$) | 1.91E+08 *Cucurbitasp.* | | | |
| | Cilantro (j year$^{-1}$) | 1.83E+07 *Coriandrum sativum* | | | |
| Total | | 3.12E+10 (j year$^{-1}$) | | | 2.60E+09 (j ha$^{-1}$) |

Transformity references for respective row number: 2. Odum, 1996, 3. Odum, 1996,4. Guillen-Trujillo, 1998, 5. Guillen-Trujillo, 1998, 6. Ulgiati et al., 1994, 7. Guillen-Trujillo, 1998, 8. Guillen-Trujillo, 1998.

3.71E10 J ha$^{-1}$ year$^{-1}$ (Table 2) which resulted in a transformity of 2.31E5 sej J$^{-1}$ (Table 4). The multiple products yielded from the polycultural system totaled 3.12E10 J year$^{-1}$ (Table 3), which resulted in a per hectare yield of 2.60E9 J year$^{-1}$ (Table 3). The emergy assigned to the yield from the polycultural system was 3.57E15 sej ha$^{-1}$ year$^{-1}$ which resulted in a transformity of 1.37E6 sej J$^{-1}$ (Table 4).

Table 4
Emergy indices for the three systems were calculated by aggregating data from Tables 1–3

| | Calculation refer to Fig. 1 | Agricultural system | | |
|---|---|---|---|---|
| | | Corn | Blackberry | Indigenous |
| Transformity (sej ha$^{-1}$ year$^{-1}$) | | 9.30E+04 | 2.32E+05 | 1.37E+06 |
| Yield (sej ha$^{-1}$ year$^{-1}$) | Y | 1.30E+16 | 8.59E+15 | 3.57E+15 |
| Total renewable (sej ha$^{-1}$ year$^{-1}$) | R | 6.56E+14 | 2.66E+15 | 3.23E+15 |
| Total non-renewable (sej ha$^{-1}$ year$^{-1}$) | N | 2.16E+14 | 0.00E+00 | 4.58E+13 |
| Total purchased (sej ha$^{-1}$ year$^{-1}$) | F | 1.21E+16 | 5.93E+15 | 2.93E+14 |
| Fraction renewable | =R/(R+N+F) | 0.05 | 0.31 | 0.91 |
| Emergy yield ratio (EYR) | =Y/F | 1.07 | 1.45 | 12.17 |
| Environmental loading ratio (ELR) | =(F+N)/R | 18.83 | 2.23 | 0.10 |
| Emergy sustainability index | =EYR/ELR | 0.06 | 0.65 | 115.98 |

### 3.5. Emergy indices

Because of the large amount of non-renewable inputs relative to renewable inputs the corn system had the lowest fraction of renewable inputs (0.05) compared to the blackberry system (0.31) and polycultural system (0.91). This indicates that the indigenous system depended on renewable resources for over 90% of its inputs. The emergy yield ratio was greatest for the indigenous system and the least for the corn system (Table 4). The environmental loading ratio is a direct inverse function of the fraction renewable (Ulgiata and Brown, 1998). The environmental loading ratio was greatest for the corn system, and the least for the indigenous system (Table 4). The emergy sustainability index was greatest for the indigenous system and the least for the corn system (Table 4). This result indicated that when considering environmental loading and yield ratios, the indigenous system outperformed the corn and blackberry production systems.

### 3.6. Sensitivity analysis

Only changes in the total emergy that resulted in increases or decreases greater than 10% in the emergy yield ratio, environmental loading ratio and emergy sustainability index were documented (Table 5). Rainfall, when doubled or halved, caused a greater than 10% difference in these values for many of the systems. For the blackberry and indigenous systems, doubling the emergy of the rainfall increased the emergy yield ratio by more than 10% (Table 5). Halving the rainfall emergy reduced the emergy yield ratio of the indigenous system by 31%. The environmental loading ratio decreased by more than 10% and sustainability index increased by more than 10% for all three systems due to doubling the rainfall emergy. Halving the rainfall emergy resulted in increases greater than 10% in the environmental loading ratio of each system. While the emergy sustainability index increased by more than 10% for each system when the rainfall emergy was doubled. Conversely, the emergy sustainability index decreased by more than 10% for each system when the rainfall emergy was reduced by 50%.

For the corn system, the only other inputs to affect these indices by more than 10% were nitrogen fertilizer and irrigation water. Doubling and halving the emergy associated with nitrogen fertilizer resulted in a 39% increase and 20% decrease in the environmental loading ratio, respectively, and a 30% decrease and 27% increase in the emergy sustainability index, respectively. Doubling and halving the emergy associated with irrigation water resulted in a 48% increase and 24% decrease in the environmental loading ratio, respectively, and a 34% decrease and 34% increase in the emergy sustainability index, respectively (Table 5).

In addition to rainfall, five inputs: irrigation water, gasoline, fertlizer, tools, and labor altered at least one of the three indices by more than 10% when their emergies were

Table 5
Results from the sensitivity analysis in which the effects of doubling and halving emergy inputs were quantified for the emergy yield ratio, environmental loading ratio and emergy sustainability index. Only changes greater than or less than ten percent of these ratios and index are noted (dashes indicate less than ten percent change)

| | | Corn system | | | Blackberry system | | | | | | Indigenous system | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Rainfall | Nitrogen fertilizer | Irrigation water | Rainfall | Irrigation water | Gasoline | Nitrogen fertilizer | Tools | Labor (non-renewable) | Rainfall | Labor (renewable) | Eroded soil | Labor (non-renewable) |
| Emergy yield ratio | Double emergy | – | – | – | 10 | 18 | – | – | – | – | 63 | 27 | – | −46 |
| | Half emergy | – | – | – | – | – | – | – | – | – | −31 | −14 | – | 91 |
| Environmental loading ratio | Double emergy | −50 | 39 | 48 | −25 | −37 | 34 | 23 | – | 22 | −41 | −23 | 14 | 86 |
| | Half emergy | 98 | −20 | −24 | 20 | 42 | −17 | −12 | – | −11 | 52 | 18 | – | −43 |
| Emergy sustainability index | Double emergy | 109 | −30 | −34 | 48 | 88 | −31 | −23 | −12 | −23 | 177 | 66 | −11 | −71 |
| | Half emergy | −51 | 27 | 34 | −21 | −36 | 28 | 18 | – | 17 | −55 | −27 | – | 236 |

doubled and halved for the blackberry system. Doubling the emergy of the irrigation water increased the emergy yield ratio and sustainability index by more than 10%, and reduced the environmental loading ratio by more than 10%. Halving the emergy of the irrigation water increased the environmental loading ratio by 42%, and reduced the sustainability index by 36%. Doubling and halving the emergy associated with gasoline resulted in a 34% increase and 17% decrease in the environmental loading ratio, respectively, and a 31% decrease and 28% increase in the emergy sustainability index, respectively. Doubling and halving the emergy associated with nitrogen fertilizer resulted in a 23% increase and 12% decrease in the environmental loading ratio, respectively, and a 23% decrease and 18% increase in the emergy sustainability index, respectively. Doubling the emergy associated with tools decreased the sustainability index by more than 10% in the blackberry system. While doubling and halving the non-renewable labor did not affect the yield ratio by more than 10%, the loading ratio and sustainability index both experienced gains and losses greater than 10% (Table 5).

Besides rainfall, three inputs, labor (renewable), eroded soil, and labor (non-renewable), altered at least two of the three indices by more than 10% when their emergies were doubled and halved for the indigenous system. Doubling the emergy of renewable labor increased the emergy yield ratio and sustainability index by more than 10%, and reduced the environmental loading ratio by more than 10% (Table 5). Halving the emergy of the renewable labor increased the environmental loading ratio by 18%, and reduced the emergy yield ratio and sustainability index by more than 10% (Table 5). Doubling the emergy associated with eroded soil resulted in a 14% increase in the environmental loading ratio, respectively, and an 11% decrease in the emergy sustainability index, respectively. Doubling the emergy of non-renewable labor reduced the emergy yield ratio and sustainability index by more than 10%, and increased the loading ratio by more than ten%. Halving the emergy of this input to the indigenous system increased the yield ratio and sustainability index by more than 10%, and decreased the loading ratio by more than 10%. The 236% increase in the emergy sustainability index when the emergy of the non-renewable labor was halved was the largest percent change across the three systems in the sensitivity analysis (Table 5).

## 4. Discussion

### 4.1. System inputs

Pimentel and Wen (1990) found that the United States invests half of its fossil energy input for agricultural production to supply irrigation water (20%) and fertilizer (30%). The results from the corn system demonstrate the continuation of this trend. Transforming all the inputs to a common basis showed an even greater percentage of energy devoted to these inputs in the corn system, where irrigation and fertilizers accounted for 95% of the purchased resources. Because water and nutrients are principal limiting factors for crop production (Pimentel and Pimentel, 1996, p. 33), farmers have large gains in yields as a result of irrigating and fertilizing. However, the increased environmental loading ratios and decreased sustainability indices indicate the dependence on external and non-renewable resources due to this investment. The higher sustainability index and lower environmental loading ratio of the blackberry and indigenous systems demonstrate the gains in sustainability and decreases in environmental loading when energy inputs for irrigation and fertilizer are reduced. Because inputs due to irrigation and fertilizer represent two of the largest energy inputs to industrialized agriculture in the United States, methods to reduce these inputs have great potential to increase the sustainability of agriculture. The sensitivity analysis demonstrated that nitrogen fertilizer and irrigation water were the two non-renewable inputs with the greatest potential to alter the loading ratio and sustainability index of the corn system (Table 5).

The technique of emergy analysis allowed energy inputs due to labor to be compared on a common basis with other inputs to each system. On a percentage basis, emergy to support labor accounted for the largest amount of purchased resources for the indigenous system (>99%) and the least amount of purchased resources for the corn system (<1%, Tables 1 and 3). This difference was demonstrated by the larger impacts of altering labor inputs in the indigenous system compared to the corn system (Table 5). These differences match trends that have been found between indigenous and conventional systems, and as agricultural systems within a country have changed over time. While 1144 h of human labor were required to produce 1 ha of corn by hand in a Mexican indigenous system (Lewis, 1951), in the United States only 10 h are expended per hectare of corn (Pimentel and Pimentel, 1996, pp. 108–116). Moving from labor-intensive to energy-intensive farming transfers much of the energy needed to support labor on the farm to labor providing purchased inputs to the farm such as fuel, fertilizer, and machinery. The far greater amount of purchased inputs and the associated emergy in the corn system compared to the indigenous system demonstrate this trend. The trend mirrors the changes in labor inputs that occur when switching from horse to tractor traction. Rydberg and Jansen (2002) showed decreased labor on the farm, but increased labor inputs to supply services and fuel as a result of this transition in Sweden.

### 4.2. Ratios

#### 4.2.1. Fraction renewable

Greater deviations from natural systems to produce crops, require greater amounts of imported energy to sustain crop production (Pimentel and Pimentel, 1996, p. 32; Altieri, 1995, p. 54). Because the indigenous system relied greatly

on natural ecological processes (Levy, 2000) it had the greatest fraction of renewable energies (0.91, Table 4). Conversely, the corn system used the greatest amount of purchased resources and the least percentage of renewable resources (Table 1), and therefore, had the lowest fraction of renewable emergy (0.06, Table 4). While natural ecosystems tend towards maturity and increased complexity, large amounts of purchased resources must be used to inhibit such changes and maintain the corn system as a monoculture with low diversity and low maturity (Altieri, 1995, pp. 54–63). The fraction renewable of the blackberry system (0.31, Table 4) indicated that it relied more on renewable resources than the corn system, but less than the indigenous system.

The amount of available renewable resources in each system affected the balance between renewable and non-renewable resources. The amount of annual rainfall in the indigenous system allows sustained crop production without the need of purchased resources to support irrigation. The corn system had the lowest annual amount of rainfall. Without the investment in an irrigation system, it is doubtful that the farm could have sufficient yields to be economically viable. The greater amount of annual rainfall in the blackberry system allows greater reliance on renewable resources, but gives the farmer the option of supplementing water during dry periods. Therefore, discussions of sustainability and reduced dependence on non-renewable resources should include careful consideration of the adaptation of a given crop to its soil and climate. The effects of altering rainfall inputs demonstrated the importance of renewable inputs, and the potential impacts of variations of renewable inputs across the three systems (Table 5).

Historically, the Lacandon Maya of southern Mexico did not have resources such as fertilizers, pesticides, commercial seeds, or machinery at their disposal. Therefore, they developed an agroecosystem with little dependence on outside resources, that was largely sustained by renewable energies. During fallow periods the Lacandon rely on natural succession to regenerate soil fertility (Diemont and Martin, 2005; Nations and Nigh, 1980). When yields begin to decrease in the milpa, or active field, the Lacandon will allow this field to undergo succession and move into the fallow stage. This regenerates soil nutrients and organic matter. In contrast, the corn farmer uses purchased resources in the form of herbicides and fertilizers to farm the same field for many years as a monoculture. In this way, many modern agricultural systems use large amounts of purchased resources to accomplish work that potentially could be performed by natural ecological processes (Altieri, 1995, pp. 89–106).

Dependence on renewable or non-renewable resources affects farmers in different ways. Heavy reliance on renewable resources makes the Lacandon very dependent upon the variability of climatic inputs, such as rain. Extended drought conditions can greatly decrease the yield from their system. While investments, such as irrigation equipment, diminish dependence on climatic events for the corn system, dependence on purchased resources makes modern farmers more susceptible to economic fluctuations (Rydberg and Jansen, 2002). In this case, the corn system could be adversely affected by changes in the amount and price of petroleum and groundwater.

Calculating the fraction renewable for each system also demonstrated the importance of the ability of emergy analysis to transform all inputs to a common basis for comparison. For instance, when comparing the raw energy input of sunlight and diesel fuel to the corn system, the joules of sunlight (3.95E15 J $year^{-1}$, Table 1) were greater than the joules of diesel fuel (1.71E11 J $year^{-1}$). However, after multiplying each of these flows by their respective transformities (Table 1), it was apparent the diesel fuel required a greater amount of solar emjoules for production (1.13E16 sej $year^{-1}$) compared to the sunlight (3.95E15 sej $year^{-1}$). This indicates that the diesel fuel is a higher quality energy, and has more potential to produce work compared to sunlight.

#### 4.2.2. Emergy yield ratio and transformity

The emergy yield ratio is especially applicable when analyzing agricultural systems where purchased resources are utilized to concentrate natural energies to produce yields. Renewable inputs of sunlight, rain, and wind are lower quality energies that are dispersed across agricultural fields. Higher quality energies from outside the system are necessary to manage the system and concentrate these energies to produce the desired outputs. The emergy yield ratio quantifies the effectiveness of purchased resources to direct renewable resources towards the production of agricultural yields. It calculates the amount of renewable emergy utilized per investment of non-renewable emergy. Systems with a higher fraction of renewable emergy, such as the indigenous system, produce a greater return per investment of non-renewable energy. The emergy yield ratio of 12.17 (Table 4) for the indigenous system indicated that more than 12 solar emjoules of renewable emergy were utilized per each solar emjoule of purchased resources invested in the system. The lower emergy yield ratio for the corn system (1.07, Table 4) indicated that a relatively small amount of renewable emergy was captured per investment of non-renewable emergy. Slightly more renewable emergy was captured per unit of purchased resources in the blackberry system relative to the corn system.

The decreased emergy yield ratios of the corn and blackberry systems compared to the indigenous system match results from conventional energy analyses of various agricultural systems. Typically, conventional energy analyses differ from emergy analyses in that energy analyses do not convert all inputs to a common type of energy (Brown and Herendeen, 1996). Contrasting from the emergy yield ratio, energy ratios compute the output of total energy divided by the input of only purchased resources. (Bayliss-Smith, 1982, pp. 40–42) found that the overall efficiency of

energy use declined as dependence on fossil fuel increased, and that the net gain of energy from industrialized agriculture was small because large amounts of non-renewable energy were expended in production. Netting (1993) documented decreasing energy ratios from 11:1 to 4:1 to less than 2:1 when comparing systems dependent on hand-labor to those dependent on animal traction and those using fertilizers and agrochemicals, respectively. The results from this analysis suggest that these declines are due, in part, to increases in the use of purchased resources and decreased reliance on renewable energies.

The lower transformity and greater yield per area (Table 4) of the corn system relative to the blackberry and indigenous systems demonstrates the benefits of investing in higher quality, non-renewable energies. The transformity results indicate that per unit of emergy input to each system, the corn system had the greatest amount of output. The higher transformities in the indigenous system were due to large losses of energy that occurred as low-quality renewable energies are concentrated to produce higher quality outputs. The higher quality inputs to the corn system have transformities similar to the output products. Therefore, less energy is lost due to energetic transformations in the production process. The use of higher quality inputs resulted in the greatest yields per area (Table 4) from the corn system. The use of fuels and machinery to distribute fertilizers and water allows for great reductions in farm labor. This allows fewer people to farm larger areas, and results in large benefits from economy of scale differences compared to smaller scale systems. In the indigenous system more area is required to concentrate lower quality energies for a smaller harvest. While the corn farmer uses the total area for production, the Lacandon rely on natural inputs and ecological succession to regenerate 10 ha of land, while using only 2 ha for production. In this manner the Lacandon concentrate renewable energies across time and space to produce yields. In contrast the corn farmer relies on the concentrated energies in fertilizers, fuels, and machinery, the make the entire crop area harvestable. In summary, these results demonstrate that the use of concentrated fossil energies and intensive cropping system are more efficient in terms of actual production (lower transformity) but less sustainable (i.e. more dependent of purchased and non-renewable flows). In contrast, when a population relies on higher fractions of more diluted but free, environmental services and products the efficiency of the actual cropping process can be lower but the system is more stable.

Reduced yields from the indigenous system also reflect the large-scale need of indigenous farmers to minimize risk and insure a minimal yield regardless of pest outbreaks or climatic inputs (Lyman et al., 1986). Investing in one high yielding variety can produce greater yields. However, past events, such as the corn and leaf blight that devastated the United States corn crop in 1970, and the potato late-blight epidemic in Ireland during the mid-19th century, illustrate the potential of such strategies to yield negligible harvests during extreme events. Research has documented that subsistence farmers will trade greater potential yields for the annual yield stability of polycultural systems (Liebman, 1995).

#### 4.2.3. Environmental loading ratio

The greater environmental loading ratios for the corn and blackberry systems compared to the indigenous system reflect the environmental costs of using more purchased resources. This ratio is directly related to the fraction of renewable resources, and is considered a measure of ecosystem stress due to production (Ulgiata and Brown, 1998). Most purchased resources create environmental degradation during their production, use, and environmental assimilation. For instance, phosphate fertilizer must be mined, transported, distributed across fields, and assimilated into the watershed. These processes disrupt natural ecosystems and release pollutants, such as $CO_2$, that require energy to degrade and assimilate. For perspective, a wilderness area relying solely on natural energies will have an environmental loading ratio near zero, while a modern city in the United States that relies heavily on imported resources may have an environmental loading ratio greater than 100 (Tilley and Swank, 2003). The dominance of renewable energy in the indigenous system resulted in an environmental loading ratio (0.10, Table 4). This finding agrees with past research that has described of the ability of the Lacandon to utilize the resources of their environment without depleting them (McGee, 2002, p. 52; Quintana-Ascencio et al., 1996; Nations and Nigh, 1980). While much lower than an urban area, the environmental loading ratio for the corn system was eight times that of the blackberry system and more than 180 times greater than the indigenous system (Table 4), and reflects a greater degree of potential environmental stress. Because environmental resources for agriculture (land, water, energy, forests) must be protected for sustained food production (Pimentel and Pimentel, 1996, p. 39), indices that quantify environmental stress due to production are essential to select future agricultural methods.

#### 4.2.4. Sustainability index

The calculated values of the sustainability index (Table 4) indicate that the indigenous system had the greatest level of sustainability followed by the blackberry and corn systems. This measure assumes that the objective function for sustainability is to obtain the highest yield ratio while minimizing environmental loading (Ulgiata and Brown, 1998). The high yield ratio and low environmental loading produced a sustainability index of 116 for the indigenous system, while the low yield ratio and high environmental loading of the corn system produced a sustainability index of 0.06 (Table 4). While the environmental loading of the blackberry system was one eighth of the corn system, a low yield ratio compared to the indigenous system resulted in the blackberry system having a sustainability index more similar to the corn system.

#### 4.2.5. Sensitivity analysis

Large changes in the emergy yield ratio, the environmental loading ratio, and sustainability index when inputs were doubled or halved (Table 5) were indicative of two factors. First, larger differences in these three values indicate where uncertainty in transformities and yearly input values would have the greatest potential to impact the results of this study. Second, examining these differences within each system, and comparing them across the three systems revealed additional characteristics of each system.

The impact of changing the emergy associated with rainfall demonstrated a high degree of sensitivity to the rainfall transformity and annual precipitation for all three systems (Table 5). Inputs of nitrogen fertilizer and irrigation water to the corn and blackberry systems were two more inputs to which the ratios and index were also sensitive. The two ratios and index were also sensitive to labor inputs in the both the blackberry system and indigenous system. The emergy yield ratio, environmental loading ratio and sustainability index were also sensitive to the emergy associated with gasoline and tools in the blackberry system, and eroded soil in the indigenous system.

A characteristic of the blackberry system was revealed by the fact that doubling and halving inputs did not cause any changes greater than 100% in the yield ratio, loading ratio, or sustainability index of this system. This demonstrated that in this system the inputs had a more equal weight compared to the corn and indigenous systems. Changes greater than 100% in the corn and indigenous system exemplified heavy dependence on rainfall and labor. The lack of labor effects upon the corn system reflected the greater amount of emergy associated with farm labor needed for the blackberry and indigenous system, compared to the corn system. The fact that doubling and halving the rainfall did not have more than a 10% effect on the emergy yield ratio of the corn system was another indicator of the greater importance of imported resources of the corn system compared to the blackberry and indigenous systems.

## 5. Conclusion

By quantifying the inputs to agricultural systems on a common basis, emergy analysis facilitates comparisons across agricultural systems and can identify manipulations to achieve greater sustainability. The corn and blackberry systems had large amounts of energy invested in irrigation, fertilizers and fuels, while the indigenous system demonstrated potential gains in sustainability by reducing the energy devoted to these inputs. Because large amounts of non-renewable energies are required to supply water and nutrients to fields, finding methods to reduce these inputs has great potential to increase the sustainability and decrease the environmental loading of agricultural production.

The yield per area of the blackberry and corn systems in relation to the indigenous system gives insight into the success of industrialized agriculture over the past half-century through the reliance on non-renewable energies. In countries like the United States, non-renewable energies, largely in the form of fossil-fuels, have been used to supply farmers with high quality inputs such as machinery and fertilizer. The results from the corn system demonstrated the increased yield per area resulting from these investments. However, the dependence on these inputs reduces the fraction of renewable energy and increases environmental degradation, making these systems less sustainable relative to systems more dependent on renewable energies.

Dependence on non-renewable energies for larger yields may be a good strategy when non-renewable energies are readily available. However, when non-renewable energy sources are no longer available, or environmental degradation prohibits their use, agriculture will need to be reorganized to rely on the limited flow of renewable resources. Results from the blackberry and indigenous systems demonstrated the gains in sustainability when this change is made. However, the decreased yields from the indigenous system demonstrated the challenge to identify food production systems with large yields that rely on renewable energies.

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